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Engineering designers' CAD performance when modelling from isometric and orthographic projections

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Abstract

The presented study investigates differences in engineering designers' CAD performance when modelling from two types of projections in technical drawings – isometric and orthographic. The results revealed significant differences in the percentage of correctly replicated components' size and shape, indicating better CAD outcomes when generating CAD models from the orthographic projection. In addition, a comparison of duration, as well as the number and type of sketch entities, sketch relations, and CAD features, showed that CAD modelling processes were similar in both conditions.

Keywords: computer-aided design (CAD), performance indicators, design representation

1. Introduction

Computer-aided design (CAD) systems, consisting of CAD software and interaction tools, are regularly employed in the contemporary engineering design process for creating, recreating, reviewing, and modifying digital versions of design representations (i.e. CAD representations; McMahon, 2015). Consequently, these systems play a fundamental role in many design activities and thus affect the engineering designer's performance – one of the essential factors determining the quality, cost, and timelines of the contemporary product development process.

Previous studies investigated and identified several factors influencing engineering designers' performance in CAD activities (i.e. CAD performance). For instance, Aranburu et al. (2022) compared CAD performance when using different modelling strategies, such as explicit reference modelling. Furthermore, Phadnis *et al.* (2021) investigated differences in individual and team-based CAD performance. On the side of the subjects' characteristics, Hamade and Artail (2008) correlated trainees' technical attributes (such as basic math, graphics, and mechanical design foundation) and CAD performance. In addition, several studies provided evidence of the relationship between engineering designers' spatial cognitive ability and CAD performance (e.g. Steinhauer, 2012). In the same line of research, several scholars found a relationship between task performance and the format of presenting the input information (e.g. Shi et al., 2020; Sweany et al., 2016). These previous studies often compared CAD models to other design representations, such as technical drawings and physical prototypes. Still, the effects of different input information formats on CAD performance remain underexplored.

Technical drawings are one type of design representation commonly used as information input to CAD modelling. Consequently, the type of projection used to present technical systems in technical drawings is one of the factors that may considerably affect engineering designers' CAD performance (Lieu and Sorby, 2016; Shi *et al.*, 2020). The presented study tests this assumption by investigating the impact of two common projection types (isometric and orthographic) on CAD modelling outcomes and processes. In particular, the study aims to answer the following research questions:

1. Does the CAD modelling outcome differ when using isometric and orthographic projections?
2. Does the CAD modelling process differ when using isometric and orthographic projections?

Both projections represent the technical systems with the same contents and amount of information. However, they represent them in different ways. On the one hand, the isometric projection is a single-view projection that represents the technical system from an angle (120°) that provides information about all three principal dimensions while each dimension is equally distorted for 30° (Lieu and Sorby, 2016; Oti and Crilly, 2021). On the other hand, multi-view projections - like the orthographic projection - contain several two-dimensional (2D) views that provide information. In particular, orthographic projection contains a set of three principal projections (front view, top view, and left side view) in the first or third angle (Oti and Crilly, 2021).
To answer the posed research questions, the paper overviews previous related work in Section 2, describes the methodology used to conduct the research in Section 3, presents the results in Section 4, and discusses the findings and limitations in Section 5. Finally, the paper concludes the findings and provides guidance for future work in Section 6.

2. Related work

Studies on engineering designers' CAD performance aimed to better understand CAD modelling processes and, consequently, enhance the outcomes. To achieve that goal, scholars have used various metrics to describe and compare CAD outcomes and modelling processes. The following subsections offer a brief overview of commonly used metrics.

2.1. CAD modelling outcome

The outcome of CAD modelling is a 3D CAD model, often evaluated in terms of its quality. Although consistently mentioned and examined in studies investigating CAD performance, CAD model quality definition as well as measurement are implicitly considered and under-discussed in previous work.
In the attempt to define and operationalise CAD model quality, Company et al. (2015) proposed six quality dimensions of CAD models: validity, completeness, consistency, conciseness, simplicity, and effectiveness and efficiency in conveying design intent. The identified dimensions are intended for educational environments and are presented as the list of rubrics that students should consider when CAD modelling to create high-quality CAD models (Company *et al.*, 2015). Besides in education, scholars have used the rubrics for research purposes. For example, Phadnis *et al.* (2021) adapted the rubrics to their experimental tasks and used them to compare CAD model quality in individual and team-based setups. Other scholars refer to these rubrics sparingly but often use metrics related to them. In most cases, they consider completeness as the accuracy in replicating the component's size and shape (e.g. Hamade and Artail, 2008; Steinhauer, 2012). In addition, editability and reusability are often explored (e.g. Chester, 2007; Diwakaran and Johnson, 2012; Rynne and Gaughran, 2008).

2.2. CAD modelling process

A CAD modelling process consists of several overt steps in which the (imagined or interpreted) geometry is first sketched in 2D using sketching entities (e.g. line, circle, etc.) that are mutually connected by sketch relations (dimensional or geometric) and then augmented into volumes by CAD features (e.g. extrude boss or cut, revolute, chamfer, etc.). The range of possible combinations of sketches and CAD features, resulting in visually equal models, is virtually unlimited (Aranburu et al., 2022). However, not all of them can guarantee high-quality CAD models, especially if considering more than one quality dimension. Therefore, studies on CAD modelling processes are often motivated by the need to identify ones resulting in high-quality CAD models.
Scholars have considered several metrics (e.g. modelling duration, number, type, and order of CAD features) to describe the modelling processes. Moreover, Gopsill et al. (2016) investigated the potential of analysing CAD logs to provide insights into the engineering designers' behaviour in design activities. In particular, they investigated the use of CAD commands (e.g. creating, editing,

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constraining, etc.), proportions of command types, and transitions between commands. Subsequently, these metrics are then used to relate CAD modelling processes and outcomes as well as to test the effect of various factors. For example, Rosso *et al.* (2021) explored the variability of the modelling process by analysing the type and order of CAD features the participants selected. Through the observed process variability, they intend to affect the editability (ability to alter the geometry easily) and reusability (ability to use the existing geometry in other contexts) of CAD models (Rosso *et al.*, 2021). Furthermore, Diwakaran and Johnson (2012) revealed differences in modelling processes depending on the task goals (ease of editability and duration). Moreover, Bhavnani et al. (1999) focus on the modelling duration and thus prefer the fewest features (but more complex ones) because such models can be modelled faster. On the contrary, scholars Rynne and Gaughran (2008) as well as Chester (2007) suggest using simpler sketches to make the models more easily edited. Similarly, Company *et al.* (2020) observed the modelling process at the sketch level by investigating the relationship between sketch relations and CAD model reusability. The number and types of sketch entities and relations have been considered less than CAD features in the previous studies, possibly because their extraction requires detailed manual analysis of the modelling process or the development of additional applications for automatising that work.

2.3. Towards the automatised extraction and calculation of metrics

There have been several attempts for automatising students' CAD performance evaluation (e.g. Garland and Grigg, 2019; Kirstukas, 2016). The available solutions are primarily intended for educational purposes to support CAD teachers in evaluating the large amounts of students' work. Calculating metrics related to evaluating the CAD outcome (e.g. volume or shape) require a "gold standard" model against which the students' CAD models can be compared. As a part of the evaluation, the users manually assign the grading weight to each metric and define the acceptable discrepancy between the "gold standard" and students' models for each of them. Considering the provided metrics within these solutions, they so far enable evaluation of validity and completeness (e.g. through the size and shape). Additionally, some applications (e.g. developed by Kirstukas, 2016) evaluate the models' editability as the ability to remain correct when the model is changed. The problem of evaluating CAD outcomes enlarges with the inclusion of quality dimensions that are more challenging to operationalise and compare with the "gold standard", such as effectiveness and efficiency in conveying design intent. Furthermore, the available solutions provide the metrics for describing the CAD modelling process (e.g. modelling duration, number and type of CAD features, number of sketches, etc.). However, users manually determine their acceptable values since they depend on the model and the modelling purpose.

To conclude, available solutions enable faster extraction of CAD data, but are limited in calculating CAD performance metrics and relating them to the CAD model quality dimensions. The main challenge when applying the available solutions outside the educational settings may be the definition of the metrics and their values so that they are representative of the expected CAD performance level. Due to the high variability of CAD model types and modelling goals, it may be that metrics cannot be universally defined but should be tailored to each modelling scenario instead.

3. Methodology

3.1. Participants

A total number of 20 mechanical engineers participated in the study. The participants' age, professional engineering experience, CAD experience, and technical drawing experience are summarised in Table 1 using their median (Med), median absolute deviation (MAD), and range. In addition, all the participants finished the same engineering graphics course as a part of their studies. Furthermore, Figure 1 presents the participants' frequency of CAD modelling and creating or reviewing technical documentation on the scale from never to always (every day).

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Table 1. Demographics, education, and prior experience

	Med	MAD	Range
Age [years]	27.50	1.34	25 - 30
Professional engineering experience [months]	21.50	16.84	0 - 72
CAD modelling in SolidWorks [months]	8	10.97	0.2 - 120
CAD modelling [% of working hours]	10	14.83	0 - 70
Creating/reviewing technical documentation with orthographic projections [% of working hours]	5	7.34	0 - 50
Creating/reviewing technical documentation with isometric projection [% of working hours]	1	1.48	0 - 35

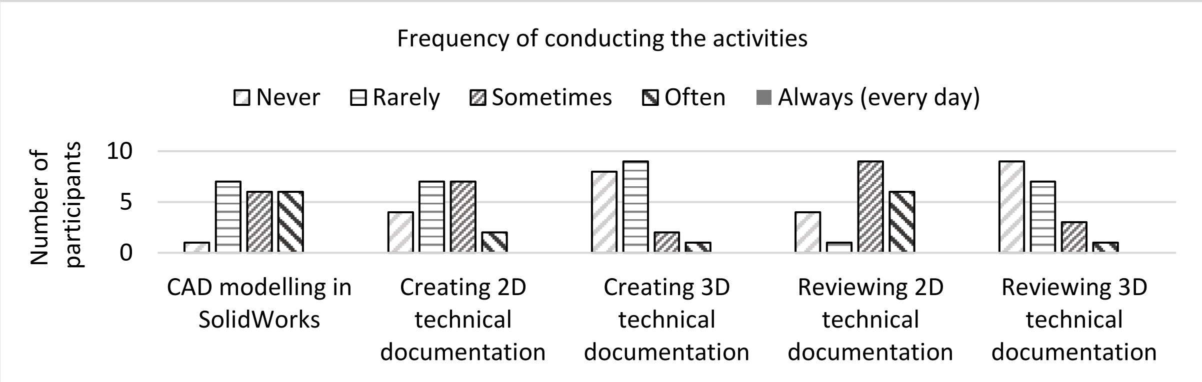

Figure 1. Frequency of CAD modelling and creating or reviewing technical documentation

3.2. Experimental procedure

The experimental procedure consisted of six main steps, shown in Figure 2. Participants were first introduced to the equipment and the procedure. In the next step, participants signed a consent. After that, participants continued to the introductory CAD task. This introductory task served as a warm-up to familiarise the participants with interaction devices and refresh their memory regarding the CAD (SolidWorks) environment before performing the main CAD tasks. Each participant performed both CAD tasks. However, the order of the conditions in which the CAD tasks were performed (isometric or orthographic projection) was controlled. Half of the participants first solved the CAD task with the isometric projection and continued to the one with the orthographic projection. The order was reversed for the other half of the participants. The CAD tasks were not time-limited. The final step of the experimental procedure was filling out the questionnaire sent to the participants via e-mail after the experiment. The questionnaire contained questions related to demographics, CAD experience and expertise, and frequency of creating and reviewing technical drawings.

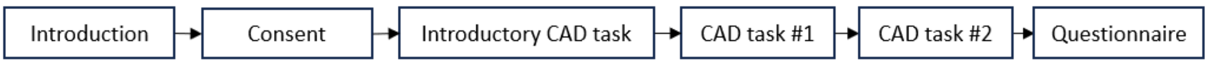

Figure 2. Experimental procedure

3.3. Experimental tasks

The study consisted of two main CAD modelling tasks in which the participants created 3D CAD models of the component from their technical drawings. The components were presented in a technical drawing with the isometric or the orthographic projection. The main goal of the CAD tasks was to replicate in 3D the size and the shape of the components presented in technical drawings in 2D. Hence, the CAD activity in this case was a transformation of design characteristics (the size and the shape) from one representation type (the technical drawing) to the other (the 3D CAD model). The complexity of the CAD modelling tasks was intentionally kept the same to mitigate the effect of using two different components. The complexity was defined based on the number and the type of geometric features the resulting 3D models consist of (Rosso *et al.*, 2021). The components, presented in Figure 3, consisted

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of the following geometric features: a cuboid, a fillet, a chamfer, a through hole, a slot, and three through slots.

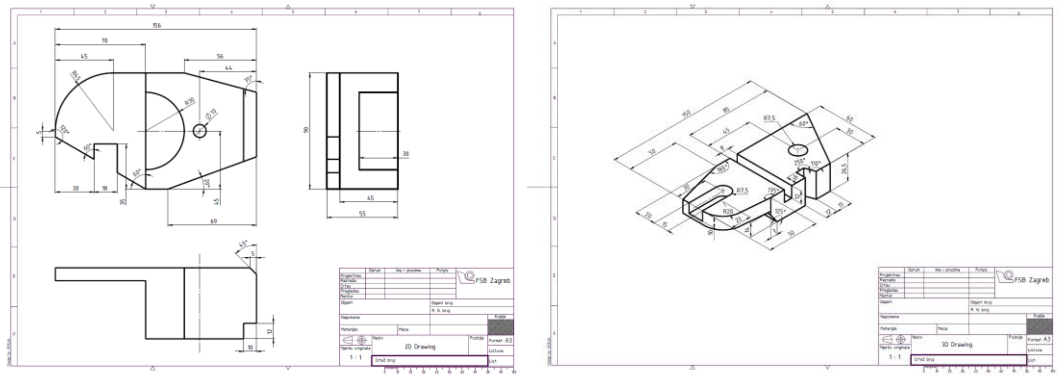

Figure 3. Technical drawings of the components

3.4. Experimental setup

The experiment was performed on one high-performance computer using two 23.8" monitor screens (resolution of 1920×1080 pixels, refresh rate of 60 Hz), a keyboard, and a mouse as the interaction devices. The left monitor screen presented the technical drawings and instructions on what should be done in each step. SolidWorks application was opened on the right monitor screen. Both screens were recorded for the entire experiment duration, thus capturing and synchronising the experimental progress from the left screen and the CAD modelling process (in SolidWorks) from the right screen.

3.5. Data analysis

CAD data for comparing the CAD outcomes and processes was extracted from two main sources: Graderworks (Garland and Grigg, 2019) and an additional application for CAD performance analysis (currently under the development by the authors). Extracted data were then analysed using the R language. Data analysis included both descriptive and inferential statistics. Descriptive statistics encompassed Med as a measure of central tendency and MAD as a measure of variability. Furthermore, inferential statistics tested differences between the isometric and orthographic conditions in CAD modelling outcomes and processes by comparing several metrics described in the following subsections. The paired t-test was used for comparisons of variables when the assumption of normality (tested by Shapiro-Wilk test; $p < 0.05$) and equity of variances (tested by Levene test; $p < 0.05$) were met. If the normality assumption was violated, the Wilcoxon signed-rank test on paired samples was used instead. In addition, the effect size of the tested differences was calculated with Cohen's d.

3.5.1. CAD modelling outcome

CAD modelling outcomes were compared based on completeness as the quality dimension. A CAD model is complete if it accurately replicates the size and shape of the component (Company *et al.*, 2015). Therefore, in each task, we compared the size and the shape of the models created by the participants with those of the "gold standard" model created by the authors. Results of the comparison (see subsection 4.1) closer to zero thus imply higher replication accuracy and, consequently, better CAD outcome. The volume and surface area of participants' models were extracted from SolidWorks using Graderworks and then compared with the "gold standard" model. Furthermore, the shape comparison was extracted directly from Graderworks, where it is performed using the D1 geometric similarity algorithm (Garland and Grigg, 2019). The algorithm is detailed in Renu and Mocko (2016), and Cardone *et al.* (2003).

3.5.2. CAD modelling process

We describe CAD modelling processes using the following metrics: total time, edit time, number and type of sketch entities, number and type of sketch relations, and number and type of CAD features the

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participants used. Edit time is calculated as a time spent on generating CAD model in SolidWorks by creating and manipulating CAD features. It was extracted using the additional application under the development by the authors. Total time stands for the entire duration of the task execution. In addition to edit time, it includes interpretation of a technical drawing based on which the geometry is then modelled in SolidWorks. Total time was extracted from the screen recordings.

4. Results

The following sections describe differences in the CAD modelling outcomes and processes between the two conditions. These differences in the following paragraphs are presented numerically in the tables and graphically in the box plots. The p-values and the related effect size are, in the following tables, coupled with the test statistic values: t for the t-test and V for the Wilcoxon signed-rank test.

4.1. CAD modelling outcome

Comparison of CAD models created by the participants with the "gold standard" model showed smaller differences in all three metrics (volume, surface area, and shape) when CAD modelling from the orthographic projection. Differences in the percentage of correctly replicated volume and shape were statistically significant, as presented in Table 2 and Figure 4. Consequently, the results indicate higher completeness (better CAD modelling outcome) when using the orthographic projection.

Table 2. CAD modelling outcomes: Completeness

Projection	Metric	Med	MAD	V or t; p	d
Isometric	Volume	-0.87	0.88	38; $1.30 \cdot 10^{-2}$	0.16
Orthographic		$-4.43 \cdot 10^{-2}$	$5.29 \cdot 10^{-2}$		
Isometric	Surface area	-0.15	0.20	67; 0.16	0.12
Orthographic		$4.13 \cdot 10^{-2}$	$7.37 \cdot 10^{-2}$		
Isometric	Shape	-3.63	2.37	32; $4.86 \cdot 10^{-3}$	0.60
Orthographic		-0.29	0.43		

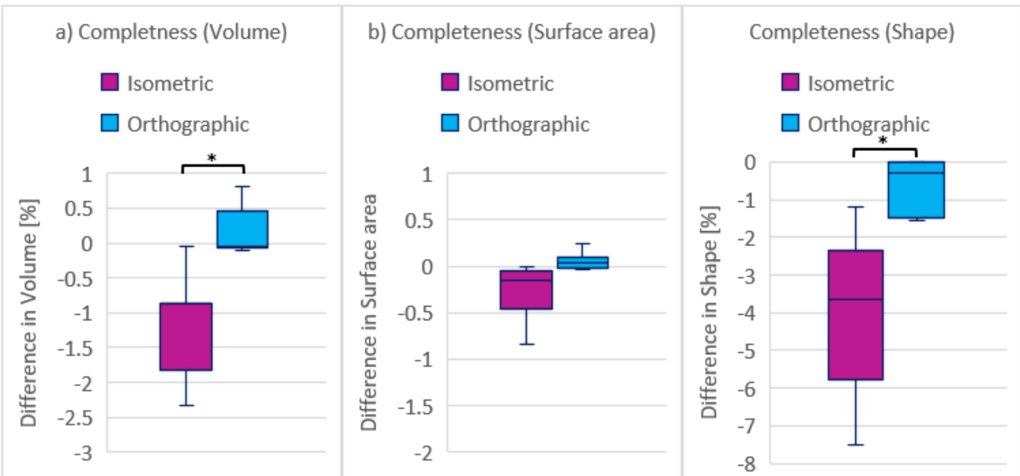

Figure 4. Completeness of CAD modelling outcomes

4.2. CAD modelling process

4.2.1. Duration

The duration of the entire CAD task performance (total time) was longer when CAD modelling from the isometric projection, as presented in Figure 5 (panel a) and Table 3. If comparing only the duration of CAD modelling, the average edit time was the same for both projections (see panel b in Figure 5).

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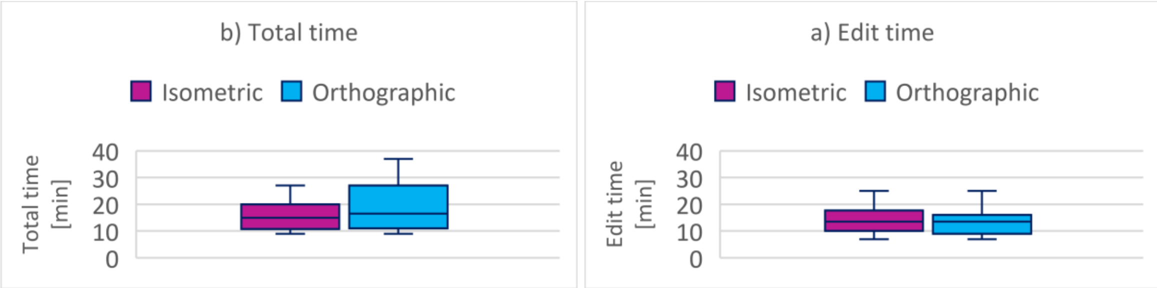

Figure 5. Total time (panel a) and edit time (panel b)

Table 3. CAD modelling process: Duration

Projection	Metric	Med	MAD	V or t; p	d
Isometric	Total time	14.77	6.00	-1.79; $9.20 \cdot 10^{-2}$	0.42
Orthographic		16.52	6.75		
Isometric	Edit time	13.50	5.19	92.50; 0.78	0.06
Orthographic		13.50	6.67		

4.2.2. *Sketch entities*

The average number of entities per sketch and the total number of sketch entities were slightly higher when CAD modelling from the orthographic projection, as presented in Table 4 and Figure 6. The most used sketch entity was *Line* for all participants in both conditions.

Table 4. CAD modelling process: Sketch entities

Projection	Metric	Med	MAD	V or t; p	d
Isometric	Average	4.92	1.36	72; 0.37	$1.84 \cdot 10^{-2}$
Orthographic		5.08	1.36		
Isometric	Total	25.00	2.97	83; 0.64	$8.15 \cdot 10^{-2}$
Orthographic		27.50	5.19		

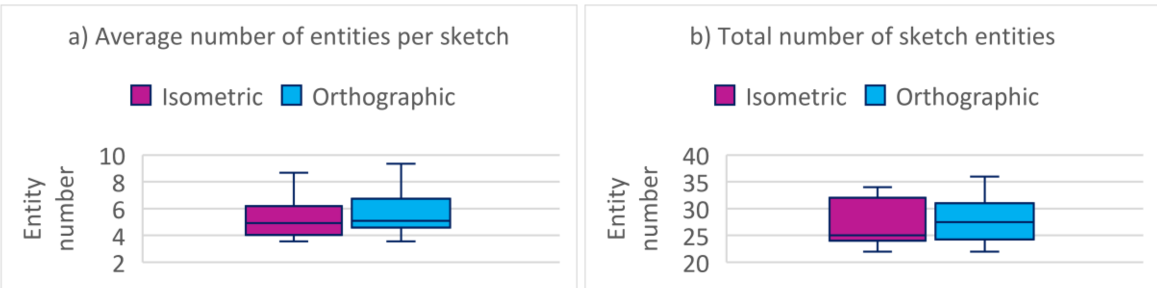

Figure 6. Sketch entities: a) Average number; b) Total number

4.2.3. *Sketch relations*

As presented in the panels and Table 5, the average and the total number of relations were slightly lower when modelling the geometry from the orthographic projection. The most used relation was *Coincident* in both conditions (see panel c in Figure 7).

Table 5. CAD modelling process: Sketch relations

Projection	Metric	Med	MAD	V or t; p	d
Isometric	Average	10.50	2.22	59.50; 0.68	0.21
Orthographic		10.00	1.48		
Isometric	Total	57.50	12.60	1.02; 0.32	0.23
Orthographic		56.50	12.60		

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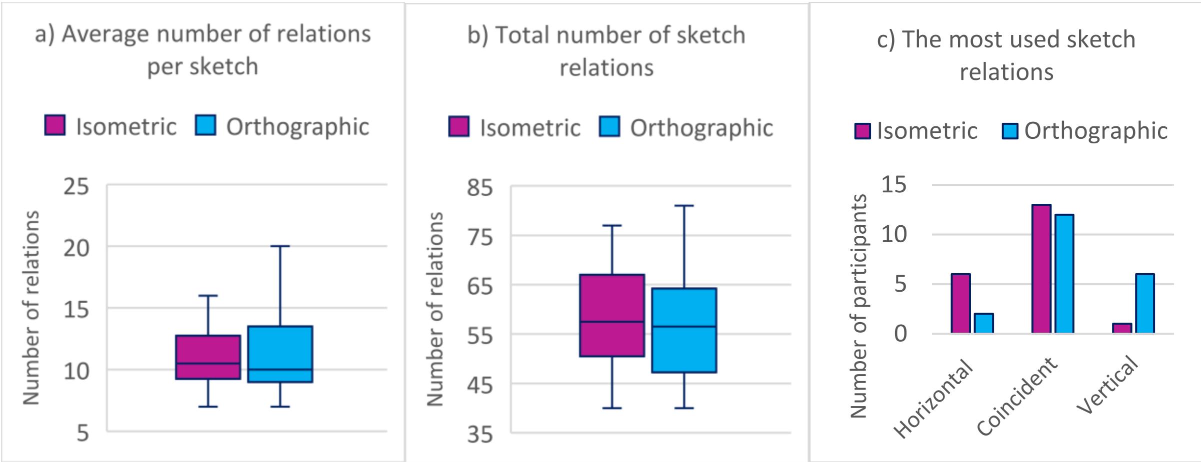

Figure 7. Sketch relations: a) Average number; b) Total number; c) The most used relations

4.2.4. CAD features

The total number of CAD features was slightly higher when generating the geometry from the orthographic than the isometric projection, as presented in Table 6 and Figure 8 (panel a). On average, the most used CAD feature was *Cut Extrude* in both conditions.

Table 6. CAD modelling process: CAD features

Projection	Metric	Med	MAD	V or t; p	d
Isometric	Number of features	5.50	2.22	-0.49; 0.63	0.11
Orthographic		6.00	1.48		

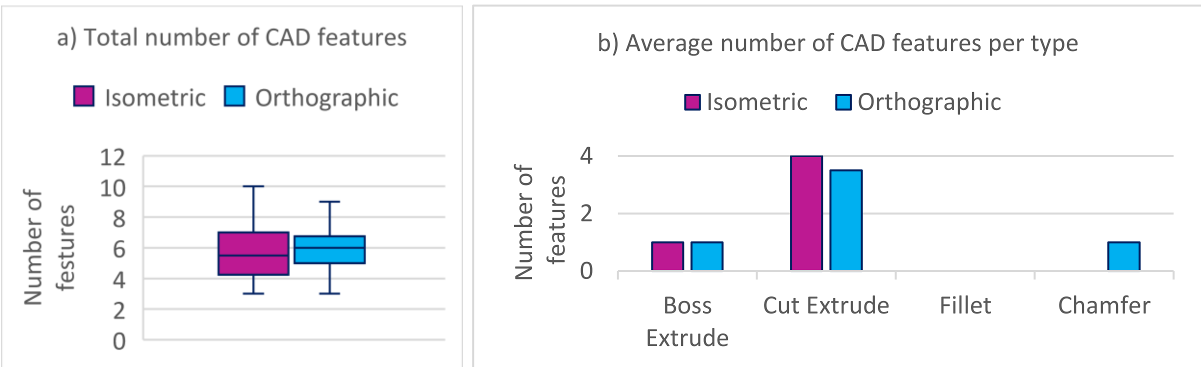

Figure 8. CAD features: a) Total number; b) Distribution per type

5. Discussion and limitations

The study builds on the previous work on CAD performance by adopting the metrics used in the literature to describe and compare CAD outcomes and processes. These metrics, initially intended for educational purposes, are here adapted to experimental tasks executed by the practitioners to compare their CAD performance in two conditions that haven't yet been explored - CAD modelling from orthographic and isometric projections.

Completeness is the quality dimension considered in the presented paper because it was the only requirement for the participants in the task instructions. The results suggest better CAD outcomes (indicated by CAD model completeness) when modelling from the orthographic projection. In particular, the higher percentage of volume and shape was accurately transformed from the orthographic projection to the 3D model than from the isometric projection. Hence, the first research question is answered positively. Such a result may be explained by the participants being more experienced in creating and reviewing orthographic projections than isometric ones, as reported in the questionnaire

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(see Table 1 and Figure 1). In addition, a comparison of the modelling duration between the conditions showed a longer total time needed to finish the task when using the orthographic projection. The edit time was approximately the same in both cases, thus indicating that participants spent more time interpreting the drawing with the orthographic than the isometric projection. It may be that this prolonged analysis of the technical drawing resulted in their better understanding of the modelling process and geometric features constituting the components, which was then reflected in the CAD outcomes. As discussed in the Related work section, Company et al. (2015) identified several other dimensions relevant for the CAD model quality assessment. Hence, the results may differ if other dimensions are considered. At the same time, including more quality dimensions might make the operationalisation of the CAD modelling process and the normalisation of metrics even more challenging due to the possible contradictions. For instance, the modelling process that optimises the fulfilment of one quality dimension could also negatively affect the others.

Furthermore, the presented study described the CAD modelling processes with several metrics extracted from SolidWorks, as it is a common practice in the field (e.g. Rosso et al., 2021). The observed differences in the CAD modelling process are less evident since the statistical significance was omitted when comparing the metrics that describe the processes. Therefore, the second research question is answered negatively - the results did not prove the differences in the modelling processes when using the orthographic and isometric projections. The possible explanation for the lack of differences lies in the components' equal complexity levels. As explained in the Methodology section, the selected components intentionally consisted of the same type and number of geometric features. At the same time, this can be seen as one of the study limitations. The differences in modelling processes may be more obvious if the components of different complexity levels are used. Additionally, it is yet to be explored if the results would be different for other components of the same complexity.

Based on the used metrics and the presented findings, we cannot claim that a particular CAD modelling process yields better CAD modelling outcomes. The metrics used to describe the modelling process will be related to the CAD outcomes in further analysis to offer the basis for comparing the processes and judging them as the better or the worse. In that way, we may recognise those processes that lead to the best (or the worst) outcomes. In the same line of research, some scholars (e.g. Rynne and Gaughran, 2008 and Chester, 2007) suggest using simpler sketches to make the models more easily modified and reused. Based on our results and this suggestion, the CAD models may be more easily modified if generated from the orthographic projection since, in that condition, participants used fewer sketch relations (thus making the sketches simpler) and more (but simpler) features. Still, this assumption should be further explored and tested.

6. Conclusions and future work

The paper compared CAD outcomes and processes when modelling two low-complexity components from their orthographic and isometric projections. The results revealed significant differences in the percentage of correctly replicated size and shape, indicating better CAD outcomes when generating CAD models from the orthographic projection. The CAD modelling process was similar in both conditions, as described using the common metrics the literature suggests. The presented findings are based on the post-task analysis of CAD data. Screen recordings will be analysed in the following studies to relate CAD features to geometric features generated in each modelling step. In addition, metrics used to describe the CAD modelling process will be related to the CAD outcomes in an effort to identify processes that yield the best or the worst outcomes. Furthermore, future work will include a real-time gathering of CAD data and subsequent conceptualisation of metrics for assessing and comparing CAD modelling processes in addition to their description. These new metrics will consider cognitive resources as an important yet empirically often neglected aspect of human performance in cognitively complex tasks such as CAD tasks.

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References

Aranburu, A., Cotillas, J., Justel, D., Contero, M. and Camba, J.D. (2022), "How Does the Modeling Strategy Influence Design Optimization and the Automatic Generation of Parametric Geometry Variations?", Computer-Aided Design, Elsevier, Vol. 151, p. 103364, https://dx.doi.org/10.1016/J.CAD.2022.103364.

Bhavnani, S.K., John, B.E. and Flemming, U. (1999), "The strategic use of CAD: An empirically inspired, theory-based course", Conference on Human Factors in Computing Systems - Proceedings, No. May, pp. 183–190, https://dx.doi.org/10.1145/302979.303036.

Cardone, A., Gupta, S.K. and Karnik, M. (2003), "A survey of shape similarity assessment algorithms for product design and manufacturing applications", Journal of Computing and Information Science in Engineering, Vol. 3 No. 2, pp. 109–118, https://dx.doi.org/10.1115/1.1577356.

Chester, I. (2007), "Teaching for CAD expertise", International Journal of Technology and Design Education, Vol. 17 No. 1, pp. 23–35, https://dx.doi.org/10.1007/s10798-006-9015-z.

Company, P., Contero, M., Otey, J. and Plumed, R. (2015), "Approach for developing coordinated rubrics to convey quality criteria in MCAD training", CAD Computer Aided Design, Elsevier Ltd, Vol. 63, pp. 101–117, https://dx.doi.org/10.1016/j.cad.2014.10.001.

Company, P., Naya, F., Contero, M. and Camba, J.D. (2020), "On the role of geometric constraints to support design intent communication and model reusability", Computer-Aided Design and Applications, Vol. 17 No. 1, pp. 61–76, https://dx.doi.org/10.14733/cadaps.2020.61-76.

Diwakaran, R.P. and Johnson, M.D. (2012), "Analyzing the effect of alternative goals and model attributes on CAD model creation and alteration", Computer-Aided Design, Elsevier, Vol. 44 No. 4, pp. 343–353, https://dx.doi.org/10.1016/J.CAD.2011.11.003.

Garland, A.P. and Grigg, S.J. (2019), "Evaluation of humans and software for grading in an engineering 3D CAD course", ASEE Annual Conference and Exposition, Conference Proceedings, https://dx.doi.org/10.18260/1-2--32764.

Gopsill, J., Snider, C., Shi, L. and Hicks, B. (2016), "Computer aided design user interaction as a sensor for monitoring engineers and the engineering design process", Proceedings of International Design Conference, DESIGN, Vol. DS 84, pp. 1707–1718.

Hamade, R.F. and Artail, H.A. (2008), "A study of the influence of technical attributes of beginner CAD users on their performance", CAD Computer Aided Design, Vol. 40 No. 2, pp. 262–272, https://dx.doi.org/10.1016/j.cad.2007.11.001.

Kirstukas, S.J. (2016), "Development and evaluation of a computer program to assess student CAD models", ASEE Annual Conference and Exposition, Conference Proceedings, Vol. 2016-June, https://dx.doi.org/10.18260/p.26781.

Lieu, D.K. and Sorby, S. (2016), Visualization, Modeling, and Graphics for Engineering Design, Vol. 148, Cengage Learning.

Oti, A. and Crilly, N. (2021), "Immersive 3D sketching tools: Implications for visual thinking and communication", Computers and Graphics, Elsevier Ltd, Vol. 94 No. 2021, pp. 111–123, https://dx.doi.org/10.1016/j.cag.2020.10.007.

Phadnis, V., Arshad, H., Wallace, D. and Olechowski, A. (2021), "Are two heads better than one for computer-aided design?", Journal of Mechanical Design, Transactions of the ASME, Vol. 143 No. 7, https://dx.doi.org/10.1115/1.4050734.

Renu, R. and Mocko, G. (2016), "Retrieval of solid models based on assembly similarity", Computer-Aided Design & Applications, Vol. 13 No. 5, pp. 628–636, https://dx.doi.org/10.1080/16864360.2016.1150708.

Rosso, P., Gopsill, J., Burgess, S. and Hicks, B. (2021), "Investigating and characterising variability in CAD modelling and its potential impact on editability: An exploratory study", Computer-Aided Design and Applications, Vol. 18 No. 6, pp. 1306–1326, https://dx.doi.org/10.14733/cadaps.2021.1306-1326.

Rynne, A. and Gaughran, W. (2008), "Cognitive modeling strategies for optimum design intent in parametric modeling (PM)", Computers in Education Journal, Vol. 18 No. 3, pp. 55–68, https://dx.doi.org/10.18260/1-2--2651.

Shi, Y., Du, J. and Zhu, Q. (2020), "The impact of engineering information format on task performance: Gaze scanning pattern analysis", Advanced Engineering Informatics, Elsevier, Vol. 46 No. July, p. 101167, https://dx.doi.org/10.1016/j.aei.2020.101167.

Steinhauer, H.M. (2012), "Correlation between a student's performance on the mental cutting test and their 3d parametric modeling ability", Engineering Design Graphics Journal, Vol. 76 No. 3, pp. 44–48.

Sweany, J., Goodrum, P. and Miller, J. (2016), "Analysis of empirical data on the effects of the format of engineering deliverables on craft performance", Automation in Construction, Elsevier B.V., Vol. 69, pp. 59–67, https://dx.doi.org/10.1016/j.autcon.2016.05.017.